VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Deividas SABAITIS

# RESEARCH OF CIRCULAR RASTER SCALES IN COMPACT DISK

## SUMMARY OF DOCTORAL DISSERTATION

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## Introduction

**Topicality of the problem.** Information systems of angle measuring and their components – raster and coded scales, rotary encoders, circular lasers are commonly used in automated machine-tools and machines, robot control systems as well as measuring and navigation devices. Linear displacement mechanisms, machines and measuring technique are analysed very well and provided with measurement technology and standards. This cannot be said about the angular measurement devices and systems. The inspection of parameters precision of angle measurement systems requires specific equipment and the use of angle standards, whereas the large variety of angle measurement systems used in modern mechanisms and devices makes this task more difficult.

This paper focuses on the assessment of the circular scale production technology's impact on the angle accuracy as well as the impact of these scales' measurement stand structure on the accuracy of angle measurement. Even though the performed research is applied to determine the precision of a specific angle measurement system, their findings have a wider range of application and can be used for creating precision systems of other use which possess new properties of good quality.

**Actuality of the work.** Lined angle measures are used as standard measures for angular displacements in machine-tools, coordinates and other measurement devices. One of their most important characteristics is the error sizes of lines' position. Their actual values can only be determined by calibration. Therefore, the production of such measures and their provision to the recognized worldwide users is only possible after solving the problem of its connection to the angle unit standard. The production ensuring calibration has to be implemented in the embedded metrology conditions i.e. when the standard calibration conditions are not provided.

The measurement analysis of raster scales and encoders demonstrates the requirements and achievements of modern measurement technology, however, these theoretical and technical problems still remain relevant in this field and need to be solved:

- the development of methods and implements for limbs and raster scales measurement, which would allow to increase the number of measured values and provide access to both discrete and analogical measurement information;
- dealing with the measurement problems of small diameter limbs and length scales of small dimensions;

– the development of new methods and implements for informational measurement systems and the increase of accuracy in angle and length measures.

**Object of research.** The dissertation research object is the new circular scales' angle measurement system. Research involves:

– the analysis of similar systems and research addressing this problem;
– the development of algorithm for lines position establishment, its analysis, optimization, solution methods for mathematical models;
– the analysis of angular errors emerging from the circular scale production technology, means and methods of their compensation.

**Aim of the work.** The main aim of this research is to create a new circular scale angular measurement system for the calibration of new type scales, which are on the base of CD and manufactured using laser technology.

**Tasks of the work.** In order to achieve the aim of the research it is necessary to find the solutions to these research problems:

1. Creating the stand of the circular scales angular measurement system, used for the calibration of the new type scales.
2. Composing the dynamic and mathematical models of the circular scales angular measurement system and perform the system modelling.
3. Analysing the typical angular errors of the circular scales, using different technology of line formation on the examined scales, and examining the production technology impact on the accuracy of circular scales.
4. Creating methodology for the evaluation of uncertainty in the circular scales angle measurement estimates results.

**Methodology of research.** Theoretical studies are based on the image processing theory, theoretical optics, mechatronics and measurement theory principles, using *Matlab*, *SolidWorks* and *OriginPro* software. Mathematical models of systems were created and analysed. Basic statistical calculations were performed using the statistical packages *Microsoft Excel* and *OriginPro*.

For the circular scales angle measurement, the optical angle measurement stand with piezo actuator and *Heidenhain* angle encoder (RON 905) was used. Also, experimental and dynamic investigations of a new mechanism for the adjustment of optical and geodesic devices using microscope NIKON MM-400 and autocollimator *Taylor Hobson precision* were created.

**The scientific novelty.** In this research paper, the following new results were obtained:

1. The circular scales angular measurement system was created for the calibration of the new type scales.
2. The impact of different line formation technology in the examined scales on the quality of the formed line in the circular scales and evaluation of the obtained angular errors.

**Practical value of research.** After the examination of literature, theoretical and physical models as well as the possibilities provided by the modern high technologies, the typical errors of the circular scales, manufactured using different production methods and were identified.

The obtained data was used for the evaluation of uncertainty in measurement result of circular scale angle measurement stand.

The findings of the research were used for the improvement of the positioning table structure which is used in the new stand of circular scales angle measurement.

**Defended propositions**

1. The circular scales angular measurement system is designed for the calibration of new type scales.
2. The composed methodology is designed for the impact evaluation of the different manufacture methods used in the production of circular scales on the accuracy of circular scales angle measurement.
3. The methodology for the evaluation of uncertainty in circular scales angular estimates measurement results.

**The scope of the scientific work.** Doctoral dissertation consists of introduction, 3 chapters and general conclusions.

The research consists of 124 pages; the text includes 103 numbered formulas, 87 figures and 18 tables. The lists of publications and literature comprise 134 items and serve an important source when working on the research study.

**The introduction chapter** is dedicated for the introduction to the problem and its topicality. It contains the formulated aims and tasks of the work, the description of the used methods as well as novelty of the solutions and presents the author's publications and structure of the thesis.

## 1. The overview of angle measurement methods. The analysis of establishing the line position

The chapter analyses angle measurement methods, optical measurement systems and the methods for line position establishment. The most modern devices for the calibration of angular measures were reviewed; the findings of research papers related to the dissertation topic were presented. The chapter ends with formulated conclusions and research objectives.

After the literature analysis, it was noticed that the topic of angle calibration is relevant and there are not a lot of research concerning the errors of calibration system of line angle measures. The literature also indicates that the structure and mathematical programme supply of each calibration system have an individual impact on the accuracy of the system; therefore, the findings of other studies may not be supported by the examined system. In order to examine the angle calibration errors it is important to:

1. Design and examine a physical model of moving image observation of line measures scale using a microscope
2. Establish the precise angle measurement calibration methodology, analytically and experimentally examine the effect of factors that influence the calibration accuracy and optimize their values.
3. Analytically and experimentally examine the influence of external and internal disturbances on the accuracy of the calibration; provide the means of reducing their impact on the calibration errors.

## 2. The adjustment mechanism for optical and geodesic devices. Analytical and experimental studies of the alignment-levelling table

Analytical and experimental studies of the new adjustment mechanism (alignment-levelling table) are presented in the chapter. The new, original data for the stability evaluation of the alignment-levelling table are obtained.

The structure of alignment and levelling: the body (outer ring), containing all other parts of the mechanism; the aligned-levelled disk (inner ring); the bottom ring used for attaching the table to other measurement systems; two alignment-levelling micro-feeds; and some elements for micro-feed transfer (springs, conical nozzles, etc.)

The adjustment table of optical and geodesic devices has two pairs of adjustment mechanisms. The position of alignment and levelling is controlled in the same plane, in the two perpendicular axes in relation to one another. This mechanism (Fig. 1 and 2) differs from the others due to the facility to simplify and increase its accuracy. Alignment-levelling micromechanisms are installed concentrically in the two perpendicular axes and their feed is transferred to the two disc thrusts. In order to increase the displacement accuracy and mechanism's resolution, both concentric mechanisms are installed in a way that allows operating independently. The alignment position is controlled via two rings 5, their surface has 0.2 mm incline and in this way they operate as concentric by moving the inner ring 2 through the shots in the right direction. Alignment is done using a microscope till the disc position corresponds to rotation position centre-wise.

The levelling position is controlled via two screw cams 4, which have conical grinded nozzles attached to their bottom 6. The screws are rotated to one side or the other, in this way the sliding conical nozzle through the shots level the inner ring 2 in the right position. The springs support the tightness and keep the disc compacted with the adjustment mechanism. Levelling is also performed while observing the object through a microscope or having an indicator leaning against it till the disc reaches its right position.

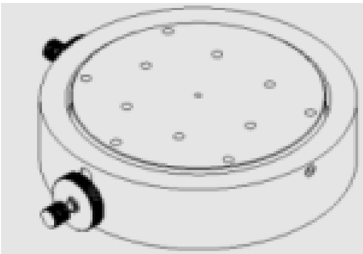


**Fig. 1.** The setting-up of the table

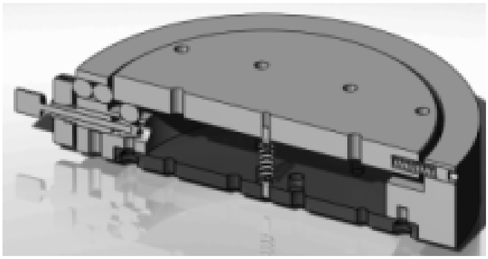


**Fig. 2.** 3D model section of the table

Theoretical justification. The system modelling was performed using *SolidWorks* programming package. When analysing the dynamic parameters of the table it is relevant to use the following formula:

$$[A]\{\ddot{q}(t)\}+[B]\{\dot{q}(t)\}+[C]\{q(t)\}=0, \quad (1)$$

where ($A$), ($B$), ($C$) – inertia, suppression and rigidity matrices; $\{q(t)\}$, $\{\dot{q}(t)\}$, $\{\ddot{q}(t)\}$ – displacement, velocity and acceleration vectors.

The modelling results are presented below. Figure 3 shows the first 7 modes of the upper part of the table.

Experimental studies of the table dynamics. The aim of these studies is to determine the mechanical instability of the system which influences the quality parameters of the system. The modal analysis, as the main evaluation of the study, is performed. For the identification of dynamic mechanical characteristics of the system, the block scheme of the study stand is given in Figure 4. Table 1 shows the comparison of theoretical and experimental results.

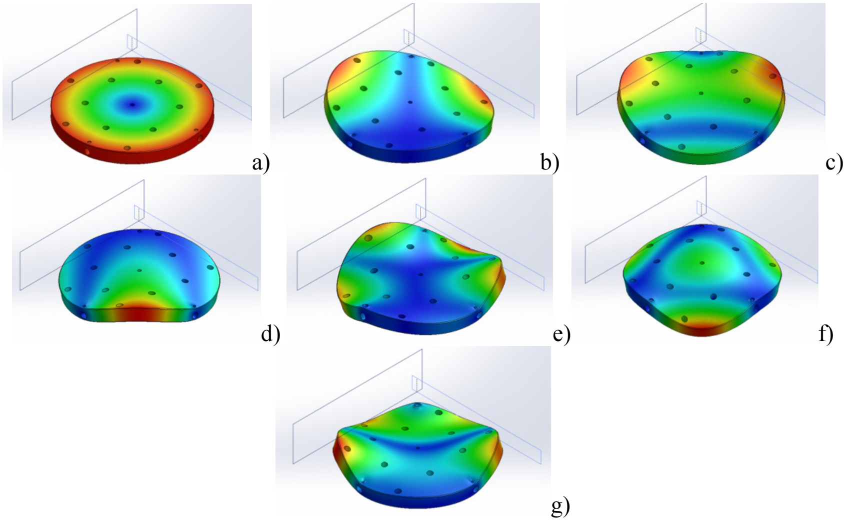



**Fig. 3.** The first 7 modes of the upper part of the table: a) the result after 298 Hz of frequency; b) the result after 431 Hz of frequency; c) the result after 593 Hz of frequency; d) the result after 1121 Hz of frequency; e) the result after 2312 Hz of frequency; f) the result after 2510 Hz of frequency; g) the result after 2623 Hz of frequency

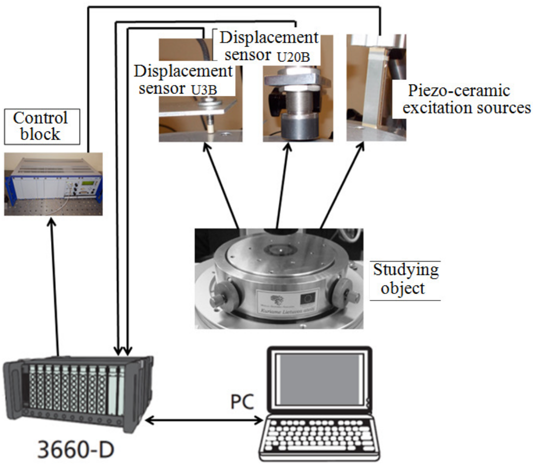


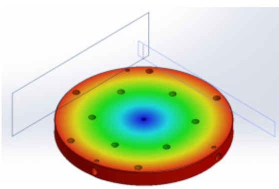
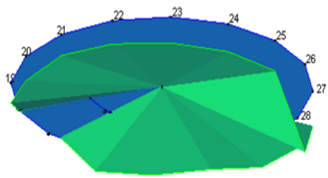
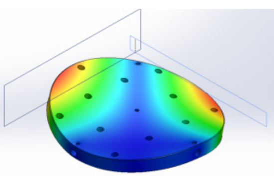
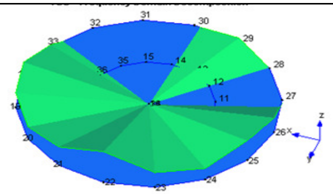

**Fig 4.** The block scheme of the study stand

The measurement results show that the dominant frequencies are: 312, 423, 570 Hz (modes 1, 2 and 3) frequencies.

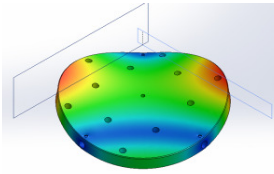
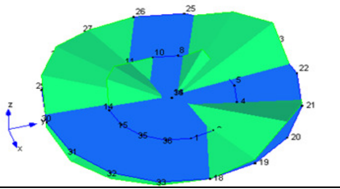
The measurements of alignment process (resolution) were performed using the NIKON MM-400 microscope of decimal micron accuracy. On the microscope, the movable table the alignment-levelling table with raster scale (made by lithographic) was placed for the measurements.

The measurement of the scale’s alignment (resolution) is done rotating the two centring screws, which are concentric to levelling screws and designed in two axes at an angle of 90°. While rotating the left centring ring (see data in Figure 5) the resolution distributes from 2 to 5 µm, after loosening the spring tension, the indicators improved to decimal places of a micrometre. Measurement uncertainty: (x) feed – 0.5 µm, (y) feed – 0.6 µm. The measurement results after rotating the right screw (Fig. 6) show that the table can be levelled at the 1–2 µm accuracy. Measurement uncertainty: (x) feed – 0.4 µm, (y) feed – 0.3 µm.

**Table 1.** The comparison of theoretical and experimental results of the modal analysis

| Modes | Theoretical | | Experimental | |
|---|---|---|---|---|
| | Frequency | Form | Frequency | Form |
| | Hz | | Hz | |
| 1 | 298 |  | 312 |  |
| 2 | 431 |  | 423 |  |

*End of table 1*

| | | | | |
|---|---|---|---|---|
| 3 | 593 |  | 570 |  |

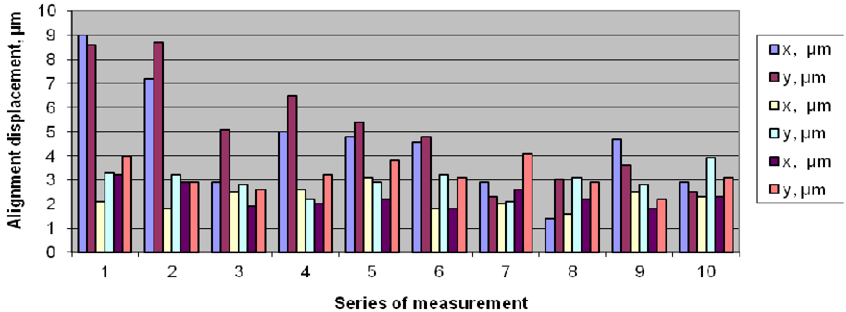



**Fig. 5.** Measurements of alignment resolution (using left ring)

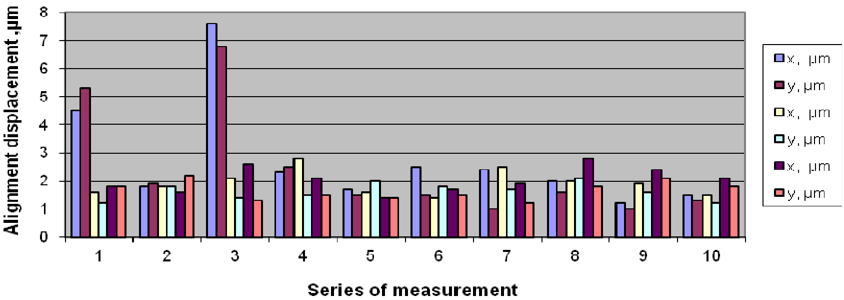



**Fig. 6.** Measurements of alignment resolution (using right ring)

The measurements of levelling process (resolution). The levelling measurements of the table i.e. the value of the α angle was determined using the 'Taylor Hobson precision' autocollimator. On the moving ring of the table a mirror was placed and the radiant of the autocollimator was diverted to it. The autocollimator acts as a connector of the autocollimator and the binocular to a one device using one objective-lens. The angle measurement between the transmitted and reflected light flow specify the reflection of the mirror surface (small mirror).

The levelling measurements were performed controlling (small) screws which are in different perpendicular axes. Rotating the screws causes the conical nozzle to push the inner ring of the table to the vertical position. The showings of the $\alpha$ angle were recorded using the autocollimator. Knowing the distance (54 mm) to the small mirror allowed the calculation of displacements using linear measures. The standard deviation – 0.45 μm (rotating the left ring) and 0.29 μm (rotating the right ring), means – 1.5 μm and 1.28 μm.

The summary of chapter 2. The developed model of angle measurement system allows the analysis of the characteristic oscillations of the angle measurement system. During the investigation of the alignment-levelling table oscillations of the angle measurement system it was ascertained that the dominant frequencies are: 312, 423, 570 Hz (modes 1, 2 and 3) frequencies.

The alignment-levelling table was designed (produced and patent) which is used for the positioning of the CD scales in the optical measurement system. The measurement analysis of the alignment-levelling table was performed using the NIKON MM-400 microscope and the autocollimator: the alignment resolution does not exceed 3 μm, the levelling has 1 μm accuracy.

## 3. The evaluation process research of the line position in the new optical step notation

A mathematical model for imaging is presented in the chapter. The physical, movement and other sources of error of the imaging system are evaluated. The new, original data of the dynamic calibration evaluation of the line positioning error were obtained.

The scales (steps) notation of the CD disc using $CO_2$ LA-7050 and Nd:YAG 50DP type lasers. While looking for an idea for a new laser-based recording and notation of the CD disc base, the two types of lasers were used:

- $CO_2$:LA60-7050 – gas laser;
- Nd:YAG 50DP – solid state laser.

In the photogrammetry laboratory, certain segments of different track positions were measured using the NIKON MM-400 microscope. The structure, symmetry and quality of steps are shown in Figures 7 and 8. The scale lines, cut using $CO_2$ laser, are obviously uneven, fragmented and do not retain the form of symmetry (Fig. 8). A result using solid state YAG laser was obtained. In this scale rasters retain the required rectangular shape and solidity. Judging from these images it can be said that the solid state laser has more advantages in the production of rasters on the CD disc base because special line margins requirements are present for the line arrangement and small line width. During the scanning of the precision scale using photoelectric measurement heads, the line margins' parameters directly influence the signal of a measurement head.

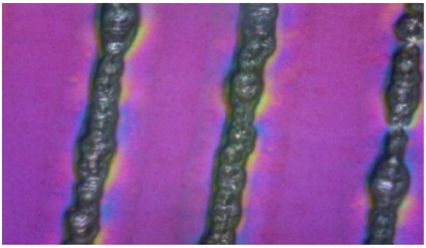


**Fig. 7.** The structure of $CO_2$ laser rasters

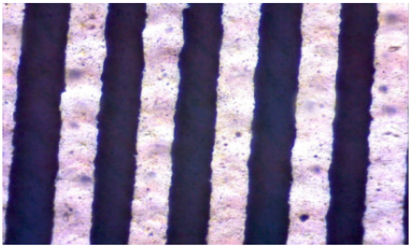


**Fig. 8.** The structure of Nd:YAG laser rasters

When measuring the width of a line, the traditional algorithm with the “parting” signal at the chosen level is the most commonly used. While rotating the camera around the optical axis before calibration, it is important to obtain a line image having the margin lines almost parallel to a column or a row of the camera sensor phototubes. A little turned two-dimensional image of the line is obtained, which, according to the algorithm, is suitable for the processing.

When using the algorithm with a marginal level it is important to obtain a two-dimensional function from a saved three-dimensional image, which would define its averaged line intensity profile. If a vertical line is examined, then the saved matrices values in each column are added and divided by the number of lines. In this way the averaged intensity curve is obtained which is called the line profile.

The accuracy of scale’s line detection depends on the illumination method, image sensor parameters, optical transfer function, image defocus and the data processing algorithm. The values of these errors are specific and depend on the structure decisions of a particular angle calibration system.

Optical measurement of raster on CD disc were performed in the laboratory of the Institute of Geodesy, at Vilnius Gediminas Technical University. The angle measurement table (Fig. 9) was used for the research, having a precise *Heidenhain* angle encoder (4), which is rotated by a piezo actuator (9). *Heidenhein* (RON 905) angle encoder has high accuracy, its resolution is ±0.4' and the scale used in the encoder has 36 000 marks. The table also has a control unit (2), which allows its rotation to both sides. On the body of this device a CD-ROOM laser head of 780 nm wavelength is installed (6). It is controlled in X, Y axes. The vertical feed can be controlled at the accuracy of 1 μm. An oscillograph (3) used for obtaining the amplitudes of measured signals is attached to the measurement system. The alignment-levelling table (5) is installed on the rotating part and a measured object is placed on it i.e. the circular scale (7).

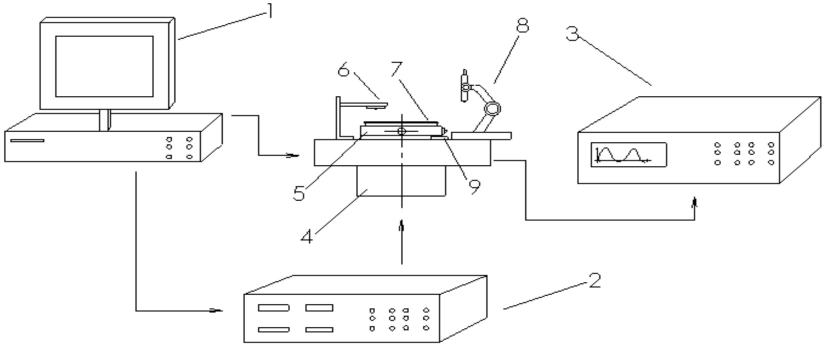



**Fig. 9.** The general principal scheme of the angle measurement (1 – computer, 2 – control unit, 3 – oscillograph, 4 – *Heidenhain* angle encoder (RON 905), 5 – alignment-levelling table, 6 – laser head, 7 – CD-type scale, 8 – microscope with a CCD camera, 9 – piezo actuator)

Figure 10 shows the CD scale measurement using NIKON MM-400 microscope. Figure 11 demonstrates CD scale of three tracks.

According to the scheme (Fig. 11) – the step length was 10 mm, and the angle between the steps is 2°.

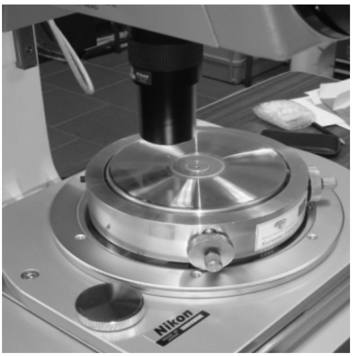



**Fig. 10.** CD scale measurement by NIKON MM-400

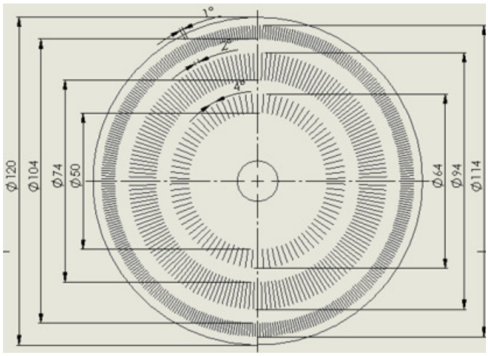



**Fig. 11.** 3 CD scale with three tracks

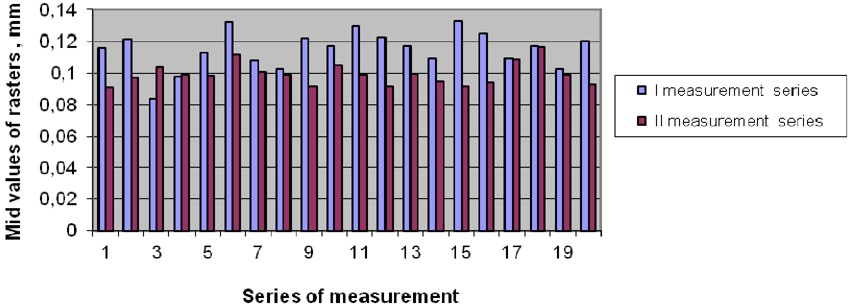



**Fig. 12.** The mid values of rasters (made by $CO_2$ laser)

After the processing of data, it was found that the mid (centre) values of the step vary by the tenth of a millimetre. The length of rasters in this scale differ up to 20 µm. The standard deviation of the lengths is 12 µm, and of the mid values of raster is 25 µm (Fig. 12).

Other measurements were performed using a scale that has 1440 lines in a circle. This scale was made using Nd: YAG laser. So we have the better result (Fig. 13) comparing with the scale made by $CO_2$ laser (Fig. 12). The minimum raster step of this scale reaches 0.17 mm. The standard deviation of the raster length is 5 µm, the standard deviation of the mid raster values is 5 µm.

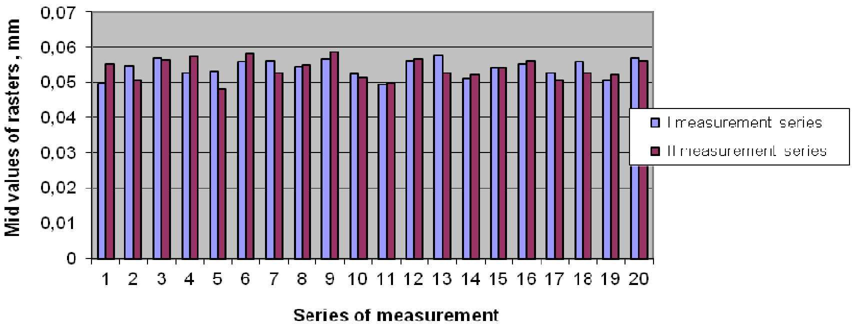



**Fig. 13.** The mid values of rasters (made by Nd: YAG laser)

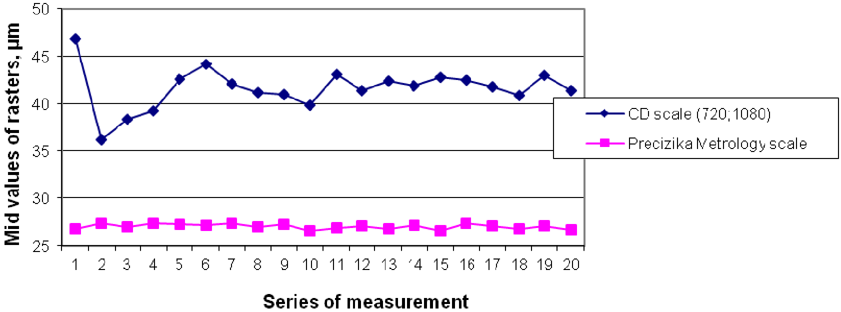



**Fig. 14.** The rasters' measurement data of different scale production technologies

For the third measurement the scale with two tracks was used: 720 and 1080 steps in the circles. The parameters of scale production cutting process accuracy were regulated with reference to the technical requirements of production and equipment. Additional levelling elements were used for the height focusing. The results – the deviation of scales mid raster values is 4.4 µm. The measurement results of the produced scale were compared to the results of the circular scale, produced by the *Precizika Metrology* company and shown in Figure 14. This company produces and provides incremental glass and coded rulers and limbs of various measurements which are used for the photoelectric measurement systems. The results of the raster parameters of different scales production.

Their production technology is completely different and the raster is formed in a thin layer of chromium which is then steamed in vacuum on a glass surface. The limbs error of the produced scales reached only 2 seconds and the scales can have a raster step up to 10 µm. The rasters' widths of the measured scale differ by 1 µm. The measurement uncertainty of the step width of the CD scale is 4 µm, while it is 0.5 µm in the *Precizika Metrology* scale. The steps' width values of the whole measurement of these different scales are shown in Figure 14. It is obvious that the manufacturer has been specialising in this field for some time and its production successfully competes in the world market.

For the evaluation of the angular error, the CD scale track with 90 rasters in the circle was chosen. Using the microscope the rasters range of sight at one time was determined. The point of threads intersection was identified with the starting point of the first raster and noted the X, Y coordinates of the point. In the *SolidWorks* programme the points were arranged in the coordinates system using 1:1 scale. The results: the angular rasters standard deviation does not exceed 40 seconds.

Figure 15 shows the distribution of this scales research data i.e. the recurrence of angle values and the size of their variations. All of this can be called the experimental error.

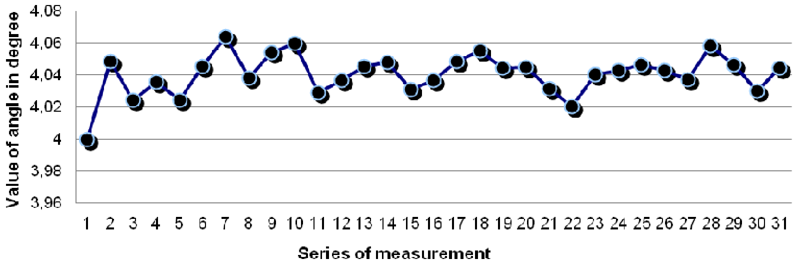



**Fig. 15.** The distribution of rasters angle values

The chapter summary. To this day the production of circular scales' rasters using laser ray is not elaborated enough to compete with the standard, quite complex and expensive mechanisms, photolithographic or other production techniques. However, the use of laser technology in the production ensures reliable, quick, good-quality result. After the evaluation of different raster production methods it is now possible to distinguish the main advantages of the laser notation of the circular scales steps:

- long-term, high-quality notation method;
- good accessibility (rough, small and complex surfaces notation);
- contactless method, no need for a special working environment;
- easy to automate and integrate;
- precision positioning (high resolution);
- high notation speed;
- significantly lower cost of production in comparison to the existing raster production method;
- no material contamination.

Optical measurements using laser measurement system were performed. Additional appliances for the facilitation of measurements were proposed. After performed calculations the uncertainty of angle measurements results was obtained – 0.43%.

## General conclusions

1. After the literature analysis of the lines' margins finding methods and the consideration of the technical properties of the equipment, a new and original line margins finding method was created. The analysis of the classic measurement methods suggests that the drawbacks of measurements encourage the creation of new methods and means for the informational measurement systems and the accuracy improvement of the angle and length measures. There should be a wider application of theoretical and practical experience while automating the measurement of raster scales and encoders. The new optical measurement systems should be improved and applied for the small diameter scales measurements.

2. After the investigation of the angle measurement system structure and the process of line detection, it was determined that the results 'uncertainty components of the linear angle measures' dynamic calibrations are related to the digital image distortion caused by motion. The minimum value of the linear measures error is obtained after the optimization of the carriage speed, scale lighting, camera exposure and its delay parameters.

3. The new optical scale measurement stand was modernized; the circular scales measurements were performed. A new circular scales alignment-levelling table was designed, produced and patented for the positioning of scales. The table is adapted to the optical scales measurement stand. The designed angle measurement system model allows the analysis of the characteristic oscillations of the angle measurement system. During the investigation of the alignment-levelling table oscillations of the angle measurement system it was ascertained that the frequencies 312 Hz, 423 Hz and 570 Hz (modes 1, 2 and 3) reduce the accuracy of measurement in the measurement process.

4. After the analysis of the circular scales production, a new optical (laser) raster notation method was presented. New circular scales were produced using the CD disc base and different laser types ($CO_2$ LA-7050 and Nd:YAG 50DP). After the analysis and calculation of the obtained results from the angle measurement system, the uncertainty of angle measurements results was obtained – 0.43%.

5. The new circular scales could be used in various mechanisms and devices for the average accuracy of angle positioning. The accuracy rates of these scales: min step of raster 45 μm and the error of raster not exceeding 20 seconds of angle.

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## APSKRITIMINIŲ RASTRINIŲ SKALIŲ KOMPAKTINĖJE LAIKMENOJE TYRIMAS

**Problemos formulavimas.** Informacinės kampų matavimo sistemos bei jų elementai – rastrinės ir kodinės skalės, kampo keitikliai, žiediniai lazeriai (lazeriniai girometrai) yra labai plačiai naudojami automatizuotose staklėse ir mašinose, robotų valdymo sistemose, matavimo prietaisuose ir navigacijos įrenginiuose. Linijinių poslinkių mechanizmai ir mašinos bei matavimo technika yra labai gerai išnagrinėti ir aprūpinti matavimo technika bei etalonais. To negalima pasakyti apie kampinių matavimų prietaisus ir sistemas. Kampų matavimo sistemų tikslumo parametrų tikrinimas reikalauja specialios įrangos ir kampo etalonų panaudojimo. Visa tai reikalauja ne tik specialios įrangos, bet ir žinių kampų matavimo raidoje, tam, kad būtų galima analizuoti bei tobulinti esamus kampų matavimo būdus, galbūt ieškoti kūrybos naujiems matavimo bei skalių gamybos būdams įgyvendinti.

Darbe pagrindinis dėmesys skirtas įvertinti naujų apskritiminių skalių gamybos technologijos įtaką kampo tikslumui bei skalių matavimo stendo konstrukcijos įtaką kampo matavimo tikslumui. Nors atliekami tyrimai taikomi konkrečios kampų matavimo sistemos tikslumo uždaviniams spręsti, jų rezultatai turi platesnę taikomąją prasmę ir gali būti panaudoti kuriant ir kitos paskirties precizines sistemas, pasižyminčias kokybiškai naujomis savybėmis.

**Darbo aktualumas.** Brūkšniniai kampo matai naudojami kaip palyginimo matai kampiniams poslinkiams staklėse, koordinatinėse bei kitose matavimo priemonėse. Viena iš svarbiausių jų charakteristikų – brūkšnių padėties paklaidų dydžiai. Realios jų reikšmės gali būti nustatomos tik kalibravimu.

Gamybą užtikrinantis kalibravimas turi būti realizuotas įterptinės metrologijos sąlygomis, tai yra, kai nesudaromos etaloninės kalibravimo sąlygos.

Rastrinių skalių ir keitiklių matavimo analizė pabrėžia šiuolaikinių matavimo technikos didelių reikalavimų gausą. Šioje srityje išlieka aktualūs teoriniai ir techniniai klausimai:

1. Limbų ir rastrinių skalių matavimo būdų ir priemonių kūrimas, leidžiantis didinti matuojamųjų verčių skaičių bei sudaryti galimybes.
2. Mažo diametro limbų ir mažų matmenų ilgio skalių matavimo problemos.
3. Naujų informacinių matavimo sistemų ir kampų bei ilgių matų tikslumo didinimo metodai ir priemones.

**Tyrimų objektas.** Disertacijos tyrimų objektas yra naujų apskritiminių rastrinių skalių kampų matavimo sistema. Tyrimas apima:

1. Panašių sistemų ir šiai problemai spręsti skirtų tyrimų analizę.
2. Brūkšnių padėties nustatymo algoritmo panaudojimą, jo analizę, optimizavimą, matematinių modelių sprendimo metodus.
3. Kampinių paklaidų kylančių dėl apskritiminės skalės gamybos technologijos įsisavinimo, jų kompensavimo metodus ir priemones.

**Darbo tikslas.** Šio darbo pagrindinis tikslas sukurti naują, kampinių apskritiminių skalių matavimo sistemą skirtą naujo tipo skalių, kurios yra ant CD pagrindo ir gaminamos naudojant lazerines technologijas, kalibravimui atlikti.

**Darbo uždaviniai.** Norint įgyvendinti darbo tikslą būtina surasti sprendimą šiems darbo uždaviniams:

1. Sukurti kampinių apskritiminių skalių matavimo sistemą, skirtą naujo tipo skalių kalibravimui atlikti.
2. Sudaryti kampinių apskritiminių skalių matavimo sistemos dinaminius ir matematinius modelius.
3. Išanalizuoti būdingas apskritiminių skalių kampines paklaidas, panaudojant skirtingas brūkšnio formavimo ant tiriamų skalių technologijas ir ištirti pagaminimo technologijos įtaką apskritiminių skalių tikslumui.
4. Sudaryti rastrinių apskritiminių skalių kampinių įverčių matavimo rezultatų neapibrėžties įvertinimo metodiką.

**Tyrimų metodika.** Teoriniai tyrimai remiasi vaizdų apdorojimo teorijos, teorinės optikos, mechatronikos ir matavimų teorijos principais, panaudojant programinę įrangą *Matlab*, *SolidWorks* ir *OriginPro.* Sukurti ir analizuoti matematiniai sistemų modeliai. Pagrindiniai statistiniai skaičiavimai buvo atlikti naudojant statistinius paketus *Microsoft Excel* ir *OriginPro.*

Apskritiminių skalių kampų matavimai buvo atlikti naudojant optinį kampų matavimo stendą su pjezo pavara bei *Heidenhain* kampo keitikliu (RON 905). Sukurto naujo optinių ir geodezinių prietaisų justavimo įrenginio eksperimentiniai bei dinaminiai tyrimai atlikti mikroskopu NIKON MM-400 ir autokolimatorium ,,Taylor Hobson precision"

**Darbo mokslinis naujumas.** Šiame moksliniame darbe gauti tokie nauji rezultatai:

1. Sukurta kampinių apskritiminių skalių matavimo sistema skirta naujo tipo skalių kalibravimui atlikti.
2. Sukurtas ir pagamintas optinių ir geodezinių prietaisų justavimo įrenginys, kuris pritaikytas tiriamos matavimo sistemos kampų matavimo tikslumo gerinimui.
3. Nustatyta skirtingos brūkšnio formavimo ant tiriamų skalių technologijos įtaka apskritiminių skalių formuojamo brūkšnio kokybei ir gautoms kampinėms paklaidoms įvertinti.

**Darbo rezultatų praktinė reikšmė.** Atlikus literatūros šaltinių, teorinių ir fizinių modelių tyrimus, o taip pat ištyrus šiuolaikinių aukštųjų technologijų teikiamas galimybes, nustatytos skirtingais gamybos būdais pagamintų apskritiminių skalių būdingos paklaidos.

Gauti duomenys panaudoti apskritiminių skalių kampų matavimo stendo matavimo rezultato neapibrėžčiai įvertinti.

Tyrimo rezultatai panaudoti naujo pozicionavimo staliuko, kuris naudojamas naujai sukurtame apskritiminių skalių kampų matavimo stende, konstrukcijai tobulinti.

**Ginamieji teiginiai**

1. Sukurtą apskritiminių skalių matavimo sistemą galima taikyti naujo tipo skalių kalibravimui atlikti.
2. Sudarytą metodiką galima taikyti skirtingais gamybos būdais pagamintų apskritiminių skalių brūkšnių padėties kampo tikslumui įvertinti.
3. Sudarytą metodiką galima taikyti apskritiminių skalių kampinių įverčių matavimo rezultatų neapibrėžties įvertinimui atlikti.

**Disertacijos struktūra.** Disertaciją sudaro įvadas, trys skyriai ir bendrosios išvados. Taip pat yra keturi priedai.

Pirmajame skyriuje išanalizuojami klasikiniai kampų matavimo būdai, įvertinti jų matavimo privalumai ir trūkumai. Didelis dėmesys skiriamas apskritiminėms skalėms, jų brūkšnio padėties įvertinimo proceso tyrimui.

Antrajame skyriuje pateikiami naujo optinio justavimo įrenginio (centravimo – gulsčiavimo staliuko) analitiniai ir eksperimentiniai tyrimai.

Trečiame skyriuje yra atliekami eksperimentiniai optiniai skalių matavimai su skirtingomis optinėmis matavimų sistemomis. Skyriuje pateikiamas vaizdo gavimo matematinis modelis. Gauti nauji, originalūs duomenys brūkšnio padėties paklaidoms įvertinti.

Darbo apimtis yra 124 puslapiai, neskaitant priedų, tekste panaudotos 103 numeruotos formulės, 87 paveikslai ir 18 lentelių. Rašant disertaciją buvo panaudota 134 literatūros šaltiniai.

**Bendrosios išvados**

1. Išnagrinėjus kampo matavimo sistemos konstrukciją ir ištyrus brūkšnio detektavimo procesą, nustatyta, kad brūkšninių kampo matų dinaminio kalibravimo rezultatų neapibrėžties komponentės susijusios su skaitmeninio vaizdo iškraipymais dėl judesio. Minimali brūkšninių matų paklaidos reikšmė gaunama optimizavus skalės apšvietimo, kameros ekspozicijos ir jos vėlinimo parametrus.
2. Modernizuotas naujas optinis skalių matavimo stendas, atlikti apskritiminių skalių matavimai. Suprojektuotas, pagamintas ir užpatentuotas naujas apskritiminių skalių centravimo-gulsčiavimo staliukas, skirtas skalėms pozicionuoti. Sudarytas kampo matavimo sistemos modelis leidžia analizuoti charakteringus kampo matavimo sistemai virpesius. Tiriant kampo matavimo sistemos centravimo-gulsčiavimo staliuko virpesius nustatyta, kad matavimo metu atsiradę dažniai 312 Hz, 423 Hz ir 570 Hz (1, 2 ir 3 modų) tiesiogiai įtakotų (sumažintų matavimo tikslumą) matavimo rezultatus.
3. Atlikus apskritiminių skalių gamybos analizę, pateiktas naujas optinis (lazerinis) rastrų žymėjimo būdas. Pagamintos naujos CD disko pagrindu apskritiminės skalės skirtingų tipų lazeriais ($CO_2$ LA-7050 ir Nd:YAG 50DP). Atlikus kampo matavimo sistemos gautų rezultatų analizę bei skaičiavimus, nustatyta kampo matavimo rezultatų neapibrėžtis 0,43 %.
4. Naujas apskritimines skales galima pritaikyti vidutinio tikslumo kampų pozicionavimui, kai minimalus rastro žingsnis neviršija 45 µm, o rastro paklaida ne didesnė nei 20 kampo sekundės.